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School of Engineering and Applied Science
The George Washington University
Washington, D. C. 20052

The program objectives are fully defined in the original proposal entitled "A Research Program in Active Control/Aeroelasticity in the JIAFS at the NASA Langley Research Center" dated August 1, 1981.

The research conducted by Dr. V. Mukhopadhyay during this report period is described below:

Development of Synthesis Methodology for Multifunctional Robust Aeroservoelastic System

Introduction

In aeroservoelastic system design of a flexible aircraft, it is often necessary to 1) obtain specified steady state structural dynamic response and to 2) maintain stablity margins at both the plant (aircraft) input and output. The design software for the latter was reported in the last progress report. The research during the present period consisted of the following two activities.

1. Formulation of steady-state structural dynamic response constraints and gradients. Tncorporation of the design software as an update to the PADLOCS synthesis software.
2. Validation of stability margin improvement technique at both the plant input and output using singular value properties and constrained optimization method.

Steady State Response Constraints (SSRC)

The steady state response is defined as the deterministic response to a step input at the plant input and/or controller input, as time goes to infinity or as the Laplace variable s goes to zero. The aircraft and servo-controller state space equations are described by equations (1) through (5) in Figure 1.

The block diagram of the closed loop system is shown in Figure 2. The two external inputs are u_{com} and v_{com} at the plant input and output respectively. The steady state responses are computed for the design output vector y_D of the closed loop system defined by equations (6) and (8). The analytical expressions for the gradients of the steady state response due to step inputs u_{com} and v_{com} are shown in equations (7) and (9). The magnitudes of the step input are specified by the vectors u_{com} and v_{com}. The designer has the option of choosing some or all of the y_D vector elements as the steady state-response constraints and must specify their maximum allowable values with proper sign.

The chosen constraints are automatically added to the original constraints on RMS response and minimum singular values. For validation and checking of the analysis by numerical computation, the drone lateral attitude control example was used. The nominal control law was modified by replacing the integrator 1/s in elevon channel by a lag network 1/(s+0.8) so that the system can reach a steady state value. The steady state response and their gradients w.r.t. controller quadruple matrices were verified against numerical time integration results.

Singular Value Shaping at Plant Input and Output

The capability of the developed design software to shape the singular value spectrum at both the plant input and output are demonstrated using the drone lateral attitude control system, as an example. The ability to shape the minimum singular value by adjusting the noise intensity matrices is illustrated in Figure 3(a) through 3(e) for a full order LQG Controller. The diagonal noise intensity matrices R_u and R_v are shown on the left of each singular value plot. In general an improved stability robustness at the plant output by increasing measurement noise intensity is accompanied by a degradation of the stability robustness at the plant input and vice-versa. Figure 3(f) shows the result of a constrained

optimization in which stability-robustness at the plant input and output were improved simultaneously using the design of figure 3(e) as the starting point.

Singular value shaping results for reduced controllers are shown in Figures 4(b) and 4(c) using the third order truncated controller design shown in Figure 4(a), as the starting point. The dashed lines in Figures 4(b) and 4(c) show the two types of desired lower bounds of singular values on which the cumulative constraint evaluation is based on. The optimization algorithm attempts to reduce the shaded area under the lower bounds to zero. The examples indicate that the constrained optimization procedure can be used to improve the stability margins at the plant input or output or, to a limited extent, at both the input and output while minimizing a performance index consisting of RMS responses.

Concise Statement of Research Accomplished

The capability of introducing two types of design constraints in the general control system design software package PADLOCS have been completed and tested. The first type of constraint is on the steady-state design-response vector due to step input. The second type of constraint is on the minimum singular value of the return-difference matrix at the plant input and output, for improving stability robustness.

Publications

1. Mukhopadhyay, V., "Stability Robustness Improvement Using Constrained Optimization Technique," Paper to be presented at the AIAA Guidance & Control Conference, August 19-21, 1985, Snowmass, Colorado.

FIG.1 STEADY STATE RESPONSE & GRADIENTS DUE TO STEP COMMAND AT PLANT INPUT

PLANT

$$\dot{x}_s = F x_s + G_u u \qquad x \to N_s \quad \cdots (1)$$

$$y = H x_s + v_{COM} \qquad u \to N_c \quad \cdots (2)$$

$$y_D = H_D x_s \qquad y \to N_o \quad \cdots (3)$$

$$y_D \to N_D \quad \cdots (4)$$

CONTROLLER

$$\dot{x}_c = A x_c + B y \qquad x_c \to M \quad \cdots (5)$$

$$u = C x_c + D y + u_{COM}$$

S.S.R.

$$\left\{ y_D \right\}_{\substack{s.s.\\ u_{COM}}} = - \left[H_D \,\vdots\, 0 \right] \underbrace{\begin{bmatrix} F + G_u D H & G_u C \\ BH & A \end{bmatrix}}_{F_a}^{-1} \begin{bmatrix} G_u \\ 0 \end{bmatrix} \left\{ u_{COM} \right\} \quad \cdots (6)$$

$$(N_D \times 1)$$

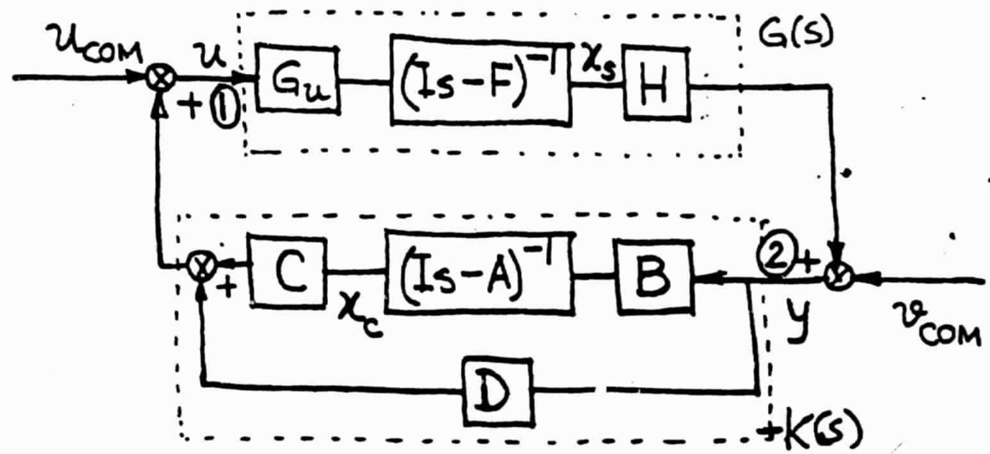
GRADIENTS

$$\frac{\partial y_{D_i}}{\partial \begin{bmatrix} D & C \\ B & A \end{bmatrix}^T}\Bigg|_{\substack{s.s.\\ u_{COM}}} = \begin{bmatrix} H & 0 \\ 0 & I \end{bmatrix} F_a^{-1} \begin{bmatrix} G_u \\ 0 \end{bmatrix} \left\{ u_{COM} \right\} \left\lfloor H_{D_i} \,\vdots\, 0 \right\rfloor F_a^{-1} \begin{bmatrix} G_u & 0 \\ 0 & I \end{bmatrix} \quad (7)$$

$$(N_o + M) \times (N_c + M)$$

FIG. 2 STEADY STATE RESPONSE & GRADIENTS DUE TO STEP COMMAND AT PLANT OUTPUT

BLOCK DIAGRAM



S.S.R.

$$\{y_D\}_{\substack{s.s.\\ v_{COM}}} = -\left[H_D \,\vdots\, 0\right] \underbrace{\left[\begin{array}{c:c} F+G_uDH & G_uC \\ \hdashline BH & A \end{array}\right]}_{F_a}{}^{-1} \left[\begin{array}{c} G_uD \\ \hdashline B \end{array}\right] \{v_{COM}\} \quad \text{--- ⑧}$$

$(N_D \times 1)$

GRADIENTS

$$\frac{\partial y_{D_{i_{s.s.}}}}{\partial \left[\begin{array}{c:c} D & C \\ \hdashline B & A \end{array}\right]^T_{v_{COM}}} = \left[\left[\begin{array}{c:c} H & 0 \\ \hdashline 0 & I \end{array}\right] F_a^{-1} \left[\begin{array}{c} G_uD \\ \hdashline B \end{array}\right] - \left[\begin{array}{c} I \\ \hdashline 0 \end{array}\right]\right] \{v_{COM}\} \left\lfloor H_{D_i} \,\vdots\, 0 \right\rfloor F_a^{-1} \left[\begin{array}{c:c} G_u & 0 \\ \hdashline 0 & I \end{array}\right] \quad \text{--- ⑨}$$

$(N_0 + M) \times (N_c + M)$

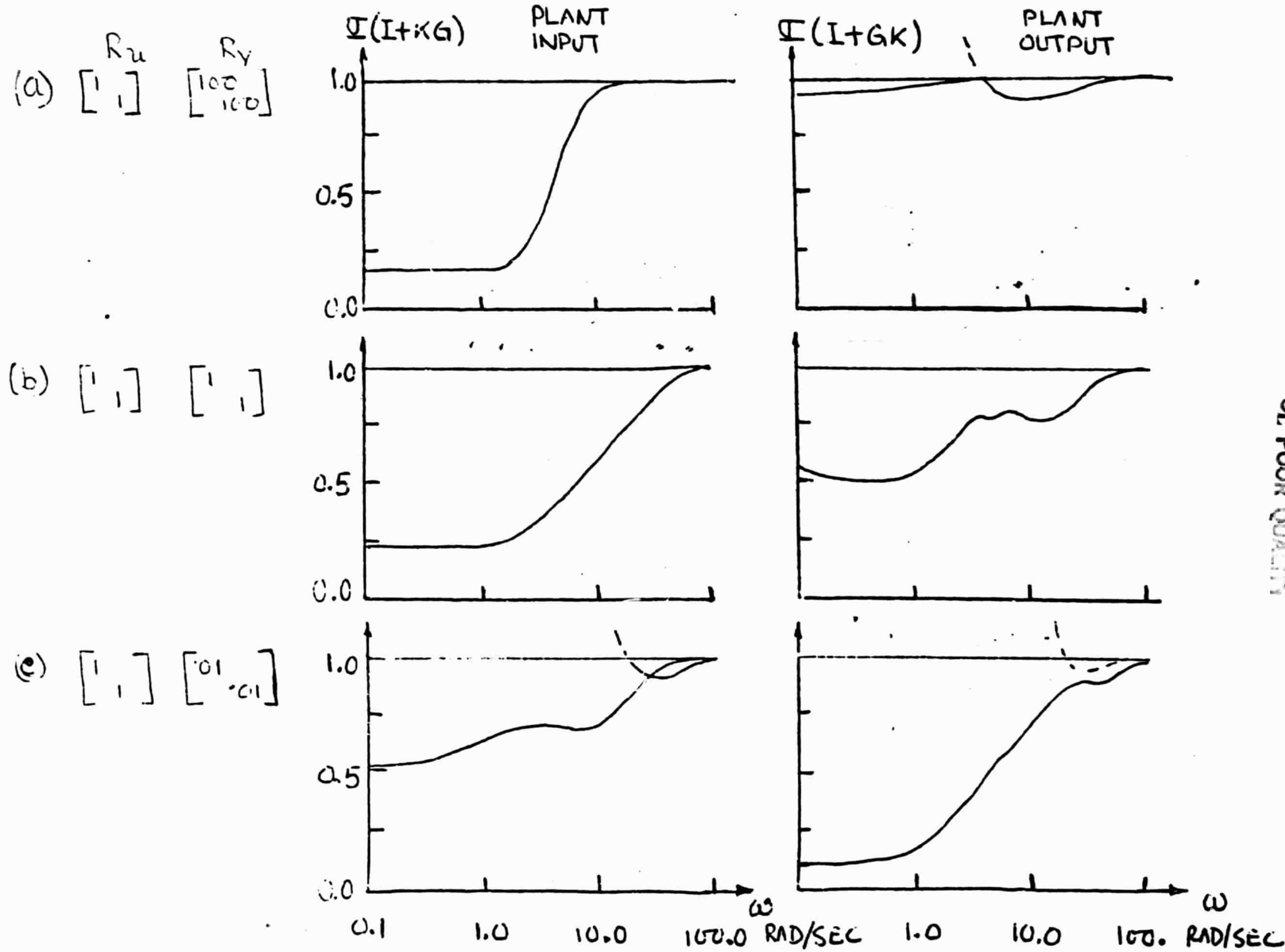


FIG. 3 SINGULAR VALUE SHAPING BY NOISE ADJUSTMENT

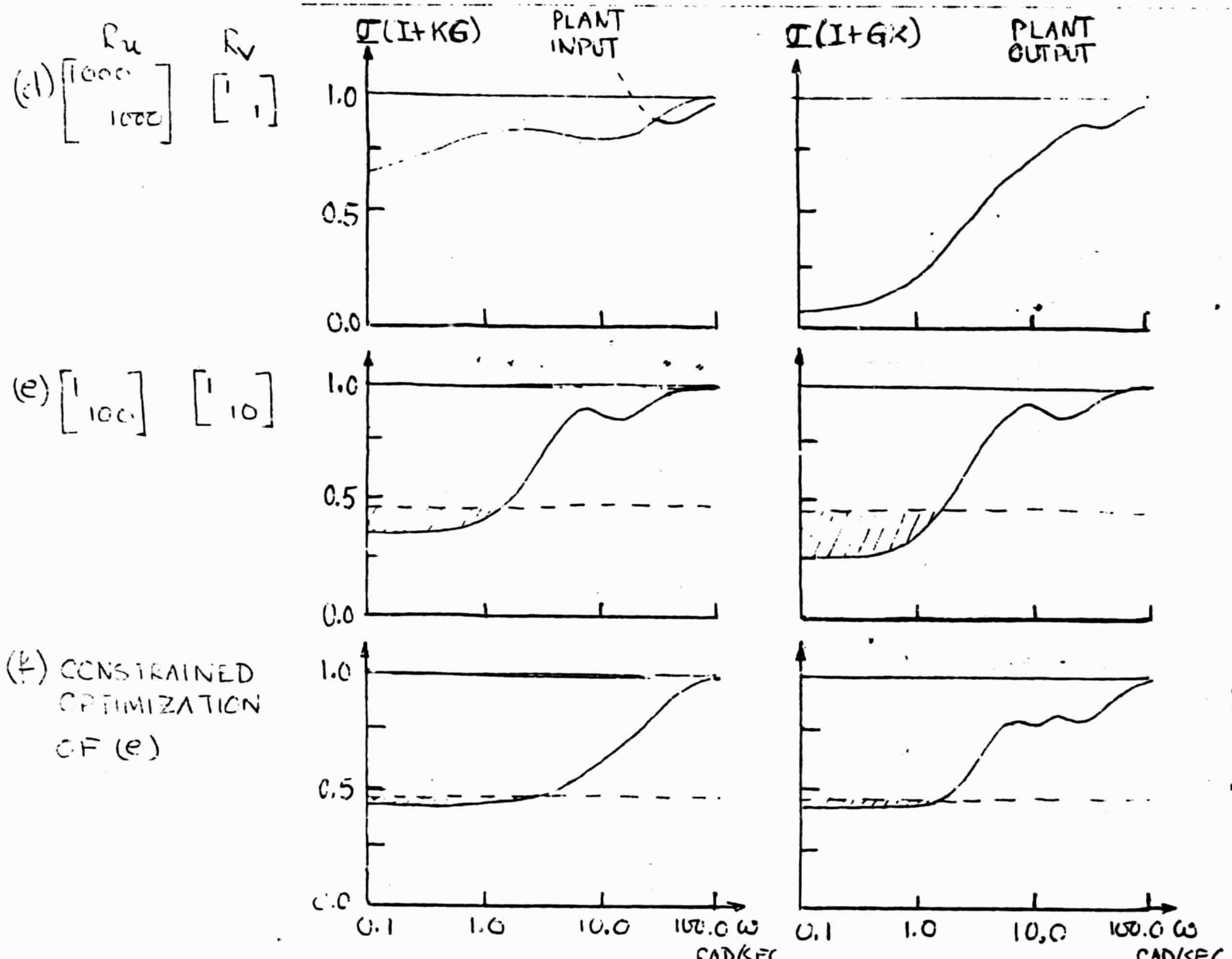


FIG. 3 SINGULAR VALUE SHAPING BY NOISE ADJUSTMENT AND CONSTRAINED OPTIMIZATION

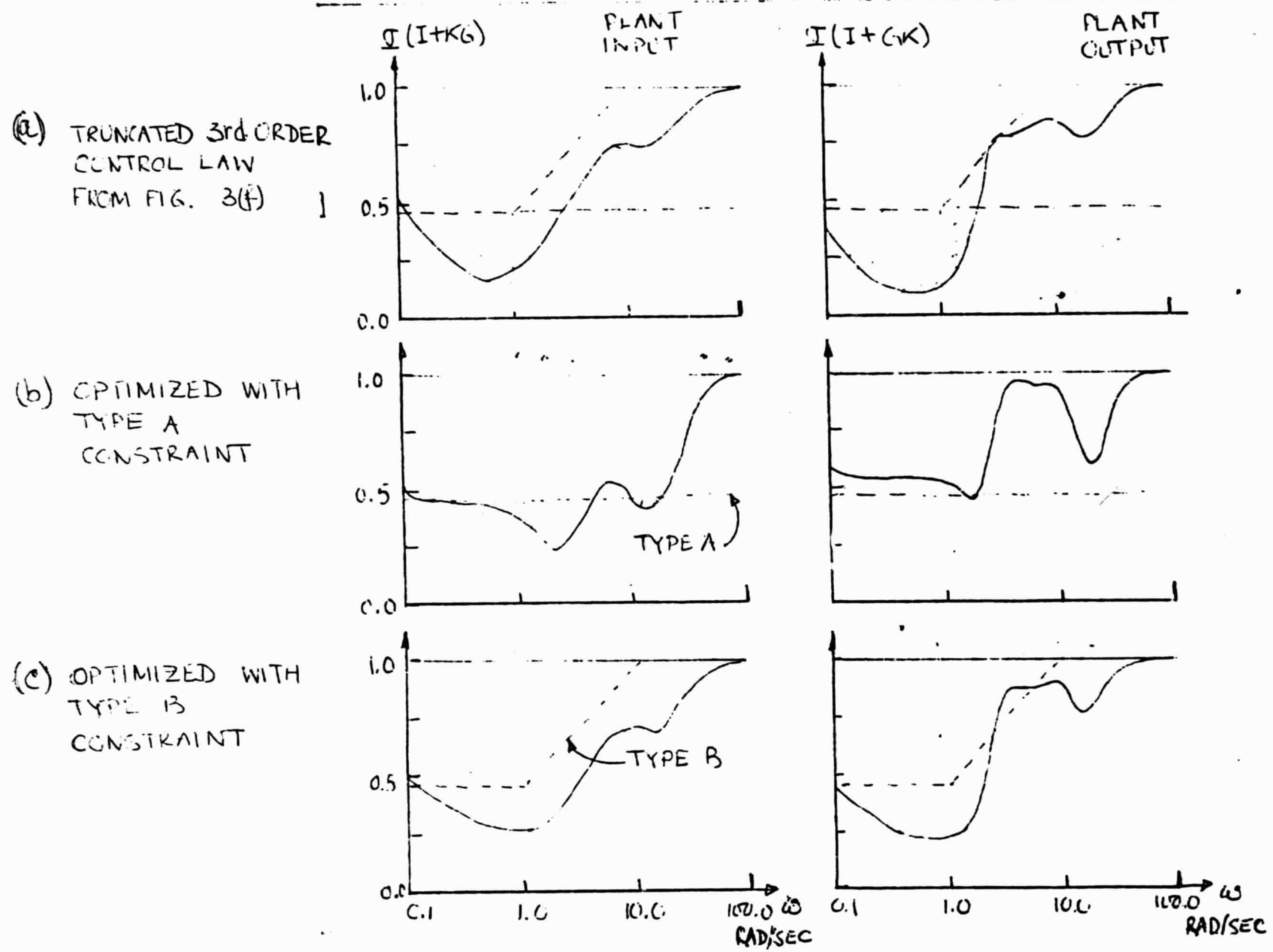


FIG.4 TRUNCATED AND OPTIMIZED THIRD ORDER CONTROL LAWS WITH TYPE A AND TYPE B CONSTRAINTS